Enhanced Predictability Through Lagrangian Observations and Analysis

PI: B. L. Lipphardt, Jr.
University of Delaware, Robinson Hall, Newark, DE 19716
phone: (302) 831-2977 fax: (302) 831-6521 email: adk@udel.edu

CO-PI: A. D. Kirwan, Jr.
University of Delaware, Robinson Hall, Newark, DE 19716
phone: (302) 831-6836 fax: (302) 831-6521 email: brucel@udel.edu

Award Number: N0014-05-1-0092
http://newark.cms.udel.edu/~brucel/slmaps

LONG-TERM GOALS

The long-term goal of this project is develop the capability to predict the origin and fate of ocean water particles. We believe that achieving this goal follows from quantification of the roles of sub-mesoscale stirring and advective transport on ocean dynamics. Spatial scales of interest range from one kilometer to the Rossby deformation scale with corresponding time scales ranging from minutes to days. We rely on synoptic currents from high-frequency (HF) radar and output from data-assimilating numerical models for information on these scales.

OBJECTIVES

Two objectives were pursued during this fiscal year.

- Study the role of the baroclinic structure of inflowing and outflowing manifolds in the formation of ocean eddies.
- Develop strategies for piloting AUVs that minimize fuel consumption and maximize time on station using information about the origin and fate of water particles.

APPROACH

We use a variety of Lagrangian based methods to quantify submesoscale advective and stirring processes from synoptic current archives. The methods are grouped into two categories. The first method is detecting and tracking the behavior of "critical" trajectories. These are usually found in regions of small velocity. Hyperbolic regions, located in the nether region between eddies, are dominated by large shear and low predictability. Material fronts or manifolds are associated with hyperbolic trajectories. Manifolds are useful in parsing the flow field into advective channels and domains where particles are segregated as long as the manifolds exist. See Kirwan et al. (2003) for a discussion of the roles they play in predictability of ocean models. Another type of critical trajectory is found in elliptic regions, typical of the centers of eddies. Here high vorticity and high predictability characterize the flow field. Kirwan (2006) provides a diagnostic conceptual model for both types of critical trajectories.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE **Enhanced Predictability Through Lagrangian Observations and Analysis**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Delaware,Robinson Hall,Newark,DE,19716**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

The other category of Lagrangian methods entails calculating the beginning to end fate of a large sample of particles. This method has led to the concept of "Synoptic Lagrangian Maps" or SLMs described in Lipphardt et al. (2006). SLMs project Lagrangian particle characteristics, such as residence times and locations of entrances and exits to regions of interest, onto Eulerian model or domain grids. During this fiscal period we began applying SLMs as a tool for AUV piloting.

WORK COMPLETED

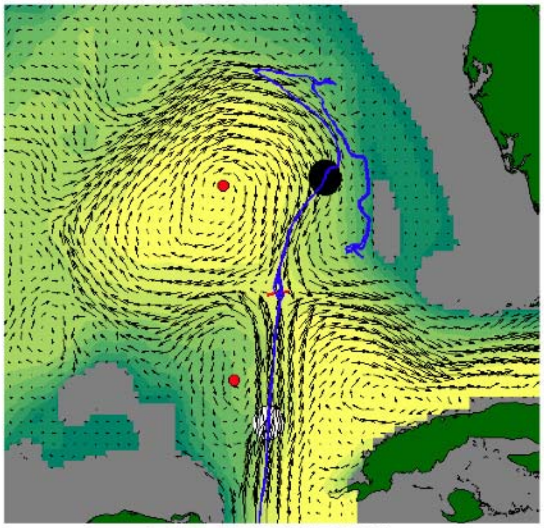
We have studied the baroclinic structure of a number of hyperbolic regions in the Gulf of Mexico using a data-assimilating numerical model and found that they extend over a significant portion of the water column. For example, using software developed on this project, Weed (2005) was able to locate hyperbolic trajcetories from the surface to 3000 meters. In Lipphardt et al. (2006) we showed the role of hyperbolic trajectories, that exist from the surface to at least 150 meters, in the abrupt break up of large ocean eddies.

We also started a preliminary investigation into AUV piloting strategies in a coastal area using archives of HF radar surface velocity measurements in Monterey Bay. SLMs based on the radar measurements identify regions in the surface flow field where long retention times exist. We have also found regions of the Bay with sharp gradients in retention time. In these sharp gradient regions, nearby AUV trajectories can have dramatically different fates.

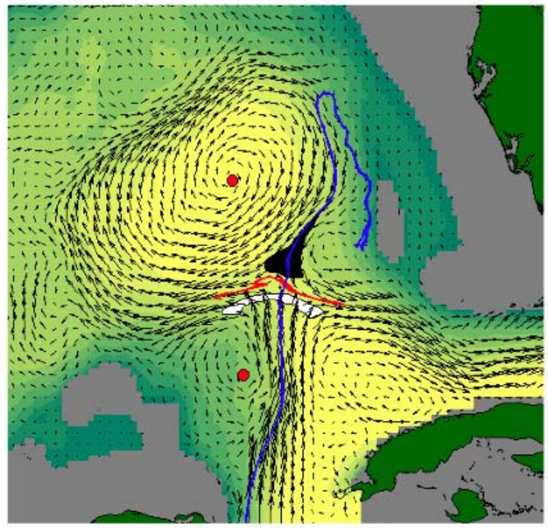
RESULTS

We note two preliminary results from research conducted over the past year. Figure 1 shows the formation of a large anticyclonic ring in the Gulf of Mexico based on velocities from a data-assimilating numerical model at a depth of 50 meters. The mechanisms causing ring pinchoffs from jets are not well understood and there is considerable uncertainty in diagnosing the time when the formation occurs. Surface information such as sea surface height or temperature suggest that many rings may undergo a series of attachments and reattachments before ultimate separation. Also, information about detachment at depth is rarely available. For this ring, we used the initial time for the development of the hyperbolic trajectory as the indicator for when the ring separated from the Loop Current. The inflowing and outflowing manifolds provide a material separatrix that denotes the formation of the ring. Note that the outflowing manifold at 50 meters wraps around the newly formed ring. For this case the hyperbolic trajectories formed at the same time at each model level down to 300m.

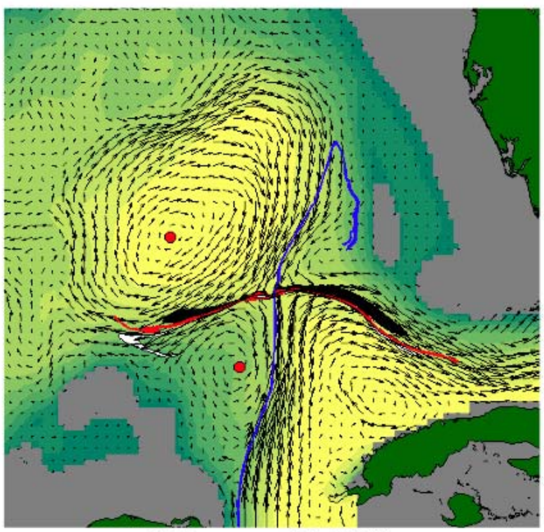
Figure 2 shows the start and end of two hypothetical AUV deployments using simple advection from archives of HF radar surface velocities during August 2005. The purpose of this calculation was to investigate environmental conditions that impact AUV navigation. Both were deployed on 2 August 2005 in Monterey Bay less than one kilometer apart. The background color is an SLM showing residence time (in days) for a grid of particles uniformly spaced at one-half km over the Bay's surface and launched on the date shown in each panel. One AUV (Figure 1d-f) beached after just 12 days. Futher analysis showed that to extend its mission and avoid beaching, it would have been necessary to expend much of its fuel to reposition within hours of deployment. Thus the fate of that mission is based on fuzzy long range predictions. In contrast, the second AUV (Figure 1a-c) stayed in the operational area for over 16 days without any need to steer. Moreover, it exited the operational area at the western open boundary.



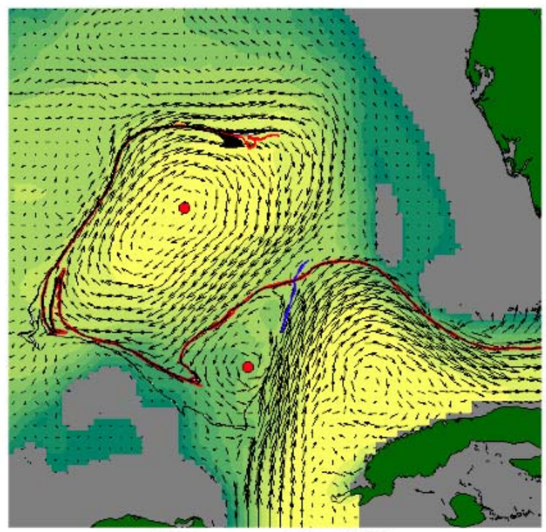
February 15, 1998



February 17, 1998



February 19, 1998



February 26, 1998

Figure 1: Sequence of images showing the pinch-off of Eddy Fourchon from the Loop Current in a February 1998 hindcast simulation from a data-assimilating Gulf of Mexico model at a depth of 50 meters. Two blobs, colored black and white, illustrate the extreme deformation that occurs as water is drawn between the Loop Current and the newly formed ring. Inflowing (blue) and outflowing (red) manifolds are also shown. Stagnation points near eddy centers are shown as red circles.

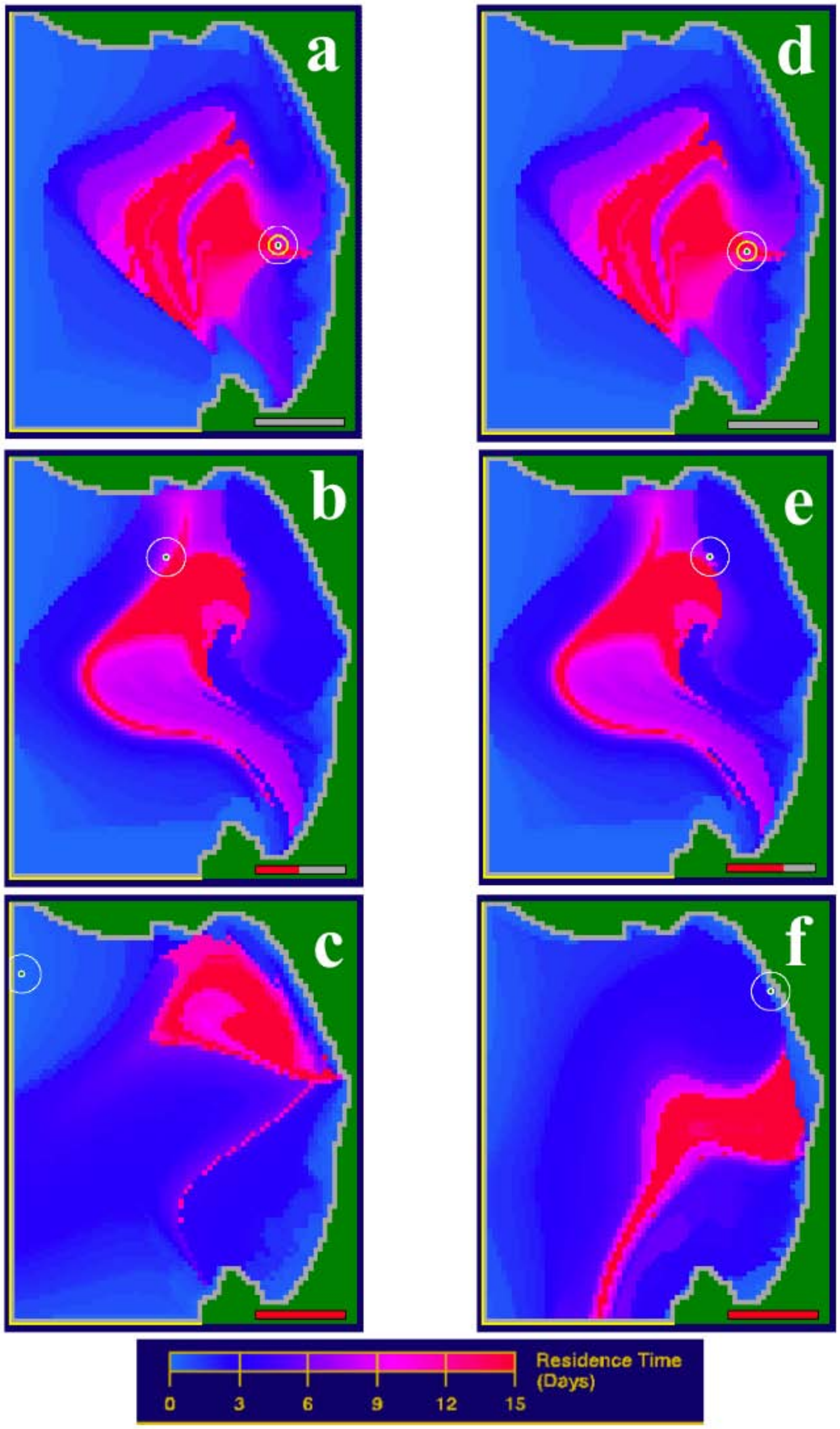


Figure 2: Evolution of two particles initially separated by less than 1 km and launched at the same time in Monterey Bay in August 2005. The first particle is shown at (a) launch; (b) after 8 days; and (c) after 16.5 days, when it escapes to the open ocean. The second particle is shown at: (d) launch; (e) after 8 days; and (f) after 12.5 days, when it reaches the coast. The background color shows residence time (in days) for particles on a regular grid, according to the color scale shown at the bottom.

IMPACT/APPLICATIONS

We feel that our results have three broad implications. The example shown in Figure 2 illustrates the importance of knowledge of the high resolution current field and the crucial role of model predictions in AUV operations. Environmental information from models or observations, on scales greater than one kilomenter, cannot distinguish between conditions that affect the two deployments, even though their fates are distinctly different.

The other two implications come from Lipphardt et al. (2006). Using velocity information from a data assimilating model of the Gulf of Mexico, they showed that hyperbolic trajectories cause the abrupt breakup of three large ocean rings in the middle of the Gulf, approximately four months after formation. This finding was quite unexpected since such features are believed to last for over a year, and model runs with no data assimilation show eddy lifetimes of the order of a year. It is stressed that specific data assimilation methodology is not an immediate issue since the data assimlation runs are well validated by drifter and hydrographic data in the eastern Gulf. Thus the second implication: does the assimilation of coarse scale altimeter data from a very active mesoscale region, such as the western Gulf of Mexico, alias the model output? Since altimeter data is now a crucial component of data assimilating models used for operational forecasts, it is important to answer this question. This will require a program with both field and modeling components. The third implication is that this result was based on Lagrangian methods developed during several years of ONR support. Traditional Eulerian based analysis methods were unable to detect the cause of the abrupt breakups. Although Lagrangian methods are relatively new in oceanography they are well established in fluid mechanics. Thus these methods offer rigorous and novel tools for model assesement.

There are two applications of this research for naval operations. First, as part of a related ONR effort, we have been applying the technology that locates critical trajectories and regions from synoptic current archives to deployment strategies for drifting acoustic sensors in the East China Sea. Second, we expect that SLMs will be useful in piloting AUVs for increased deployment times and area coverage in coastal and littoral environments.

RELATED PROJECTS

The research performed on this grant is closely related to ONR grant N00014-00-1-0019. That grant applies many of the techniques used in this study to velocity and hydrodynamic fields from a Navy data-assimilating model of the East Asia Seas area (EAS16). The PI and CO-PI of the present grant are also the principals on the latter grant.

REFERENCES

Kirwan, A. D., Jr., M. Toner, and L. Kantha, Predictability, uncertainty, and hyperbolicity in the ocean, *International Journal of Engineering Science*, 41, 249-258, 2003.

Weed, M., The anatomy of hyperbolic trajectories in the Gulf of Mexico, M.S. Thesis, University of Delaware, 2005.

PUBLICATIONS

Kirwan, A. D., Jr., Dynamics of "critical" trajectories, *Prog. in Oceanogr.*, 70, 448-465, 2006.

Lipphardt, B. L., Jr., D. Small, A.D. Kirwan, Jr., S. Wiggins, K. Ide, C. E. Grosch, and J. D. Paduan, Synoptic Lagrangian maps: Application to surface transport in Monterey Bay, *Jour. Mar. Res.*, 64, 221-247, 2006.

Lipphardt, B. L., Jr., A. Poje, A. D. Kirwan, Jr., L. Kantha, and M. Zweng, Sudden death of Loop Current rings in a data-assimilating Gulf of Mexico model, *in review.*